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REVISED AIRCRAFT LOAD CURVES AND VEHICLE ICE-THICKNESS TABLES FOR ANNUAL ICE SHEET OPERATIONS NEAR MCMURDO, ANTARCTICA

By

K. D. Vaudrey

April 1976

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Updated aircraft load curves and vehicle ice-thickness tables are presented for operations on the sea-ice sheet near McMurdo Station, Antarctica. First, material property research on sea-ice is reviewed to demonstrate the current knowledge of ice-sheet bearing strength. Then the elastic finite element computer code is discussed: how it models an ice sheet and accepts material property and loading condition parameters.

The load curves and ice-thickness tables give minimum ice-sheet thicknesses for specified aircraft and vehicle weights over four seasonal periods during the operating season. In addition

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INTRODUCTION

Existing floating sea ice sheets in the polar regions have been utilized to support surface and air operations. Adequate airfields and ice roads can be economically constructed and maintained on annual sea ice; for example, the sea ice near McMurdo Station, Antarctica, has been used each season since the International Geophysical Year (IGY). However, the operating criteria must be updated as research continues to provide an increased understanding of the overall behavior of an ice sheet.

This report presents a new series of allowable load versus ice-thickness curves for both C-130 and C-141 aircraft and updated tables of minimum allowable ice thicknesses for many different vehicles operating near McMurdo Station. Both curves and tables are intended to supersede those presented in CASAINST 3710.2G, Chapter 1, Section V, currently used as operational guidance criteria [1]. The aircraft load curves and the ice-thickness tables for vehicles presented in this report have replaced empirical and plate solution techniques used previously [2,3] by employing an elastic finite element method for predicting sea-ice sheet behavior. Results and experience from an extensive experimental program are incorporated into the finite element computer code and are the basis for establishing failure criteria and setting appropriate safety factors.

MATERIAL PROPERTIES OF SEA ICE

Temperature, salinity, and age each affect the bearing strength of an ice sheet. The combined effect of these parameters generally results in anisotropic behavior vertically through an ice sheet. Fortunately, for a short-term operation between October and February on the McMurdo annual sea ice, the only variable in strength analysis is temperature. During this short period there is no appreciable change in ice properties from salinity variation and aging. Salinity profiles of the ice sheet taken during the operational period are fairly constant. The salinity profile from year to year also varies little because the sea-ice runway and ice roads generally are located on annual ice.

Therefore, only temperature-dependent material properties of sea ice have to be defined. The ice temperature near the top surface specifies the thermal gradient in an ice sheet, since the temperature at the bottom approximates the freezing point of seawater (28.8^{o}F). This gradient can be assumed to be linear for the purpose of practical application.

Division of the ice conditions during aircraft and vehicle operations into four thermal time periods logically reflects the effect of progressive warming and internal melting on the material properties and resulting lower strength of the ice sheet. In periods one and two (Figure 1), strength deterioration results from decreasing the temperature gradient or general warming of the ice sheet. During period four, strength deterioration is due to a stagnation at an isothermal condition (near-melting temperature). Both the later phase of general ice sheet warm-up and beginning phase of internal melting are included in period 3.

Prior to analyzing the ice-sheet behavior, both the flexural strength and modulus of elasticity properties of sea ice must be determined as a function of ice temperature. The following discussion presents a brief summary of a portion of the sea-ice experimental program undertaken by the Civil Engineering Laboratory (CEL).

Flexural Strength

Both laboratory and field experiments were performed to determine the flexural strength of sea-ice beams [4,5]. All laboratory and small field beams were simply supported and had nominal dimensions of 2 x 2 x 16 inches. On the other hand, large field specimens were tested in-situ as either cantilever or simply supported beams having a cross-sectional width of 35 to 40 inches, a depth of 60 to 95 inches, and a length of 35 to 90 feet. A summary of the results, representing a complete strength-temperature history for sea-ice beams appears in Figure 2. The data span a temperature range of $-2^{o}C$ to $-28^{o}C$. Each field strength datum point is plotted at the average temperature for beams having a thermal gradient, while the average of each isothermal laboratory group is shown with 95% confidence limits on the mean.

Modulus of Elasticity

In addition to the flexural strength, the single most important material property of sea ice is the modulus of elasticity. The easiest method for finding this modulus is to measure the strain corresponding to a given stress state in a right circular cylinder subjected to either pure compression or tension. Over 300 compression specimens with a length-to-diameter ratio of 2.0 were tested in the laboratory at four different ice temperatures and for both vertical and horizontal crystal orientation. Deflection measurements were recorded by extensometers, having a gage length of 2.375 inches, bonded directly to each specimen with freshwater ice. The tests were performed on specimens cored both perpendicular to (horizontal) and parallel to (vertical) the direction of crystal growth. The results of these modulus of elasticity tests are shown in Figure 3. The values for the modulus of elasticity are not only temperature-dependent but are considerably greater for ''vertical'' sea-ice specimens than for ''horizontal'' specimens.

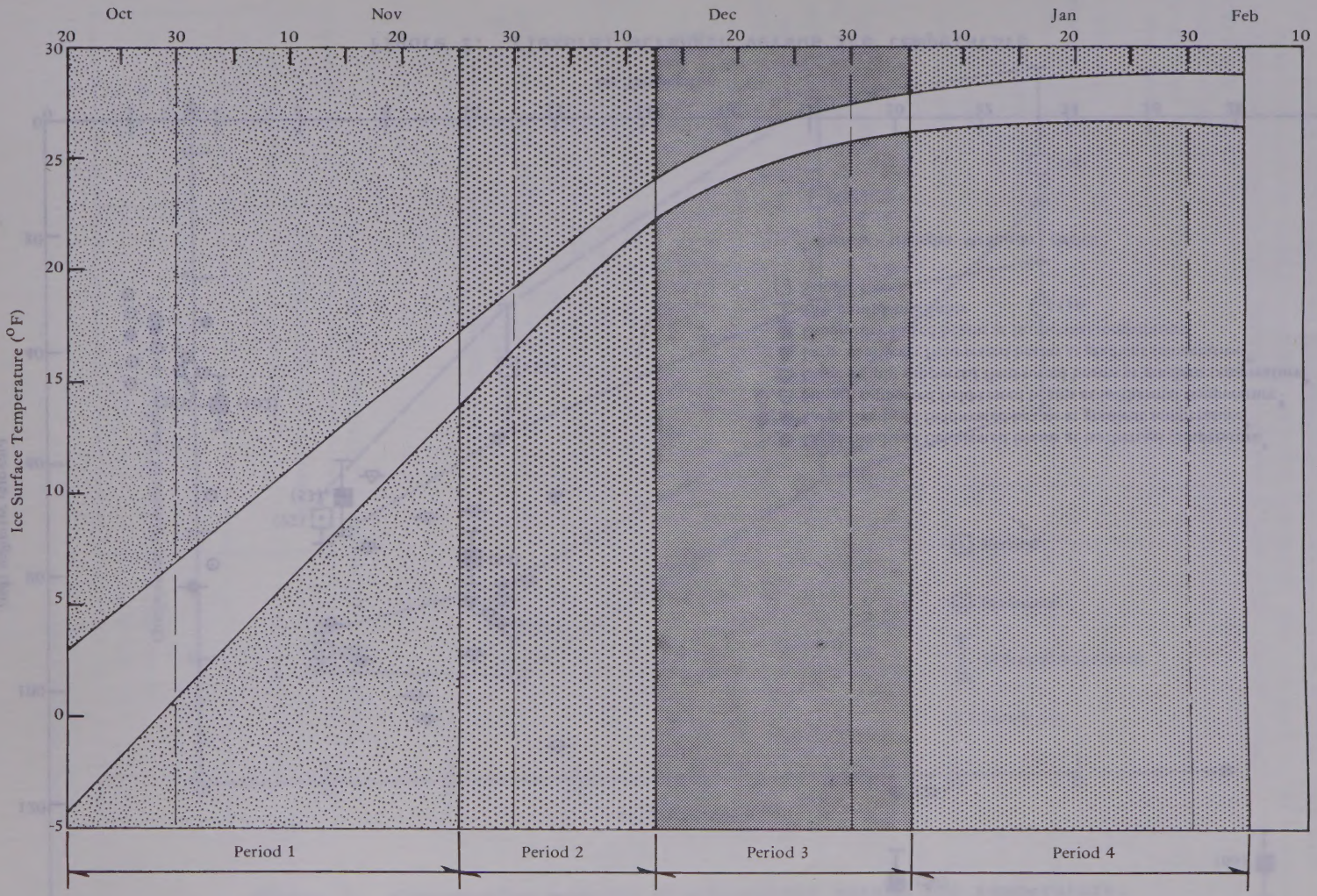

Figure 1. Near-surface temperature of McMurdo annual sea ice for normal operating season.

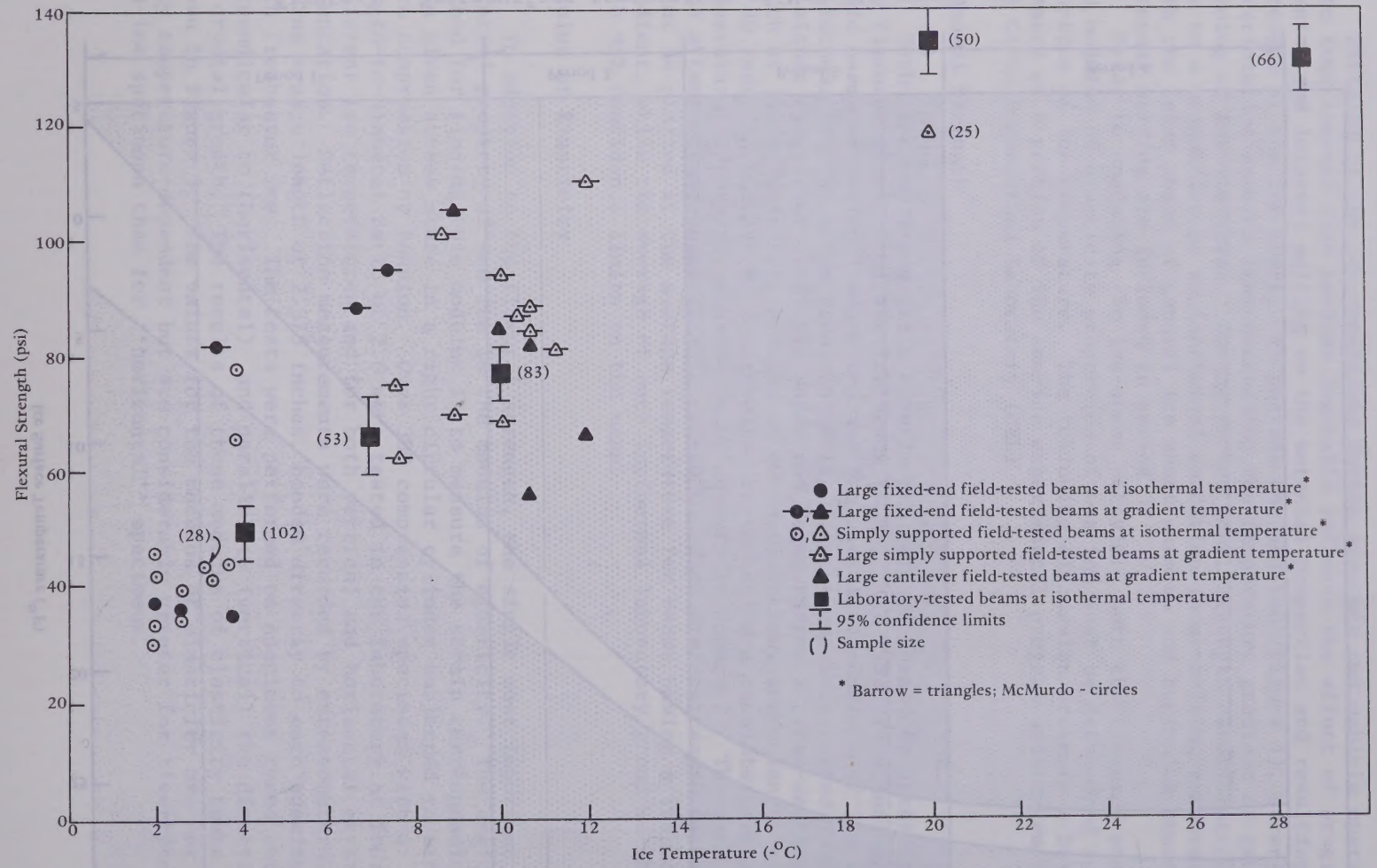

Figure 2. Flexural strength versus ice temperature

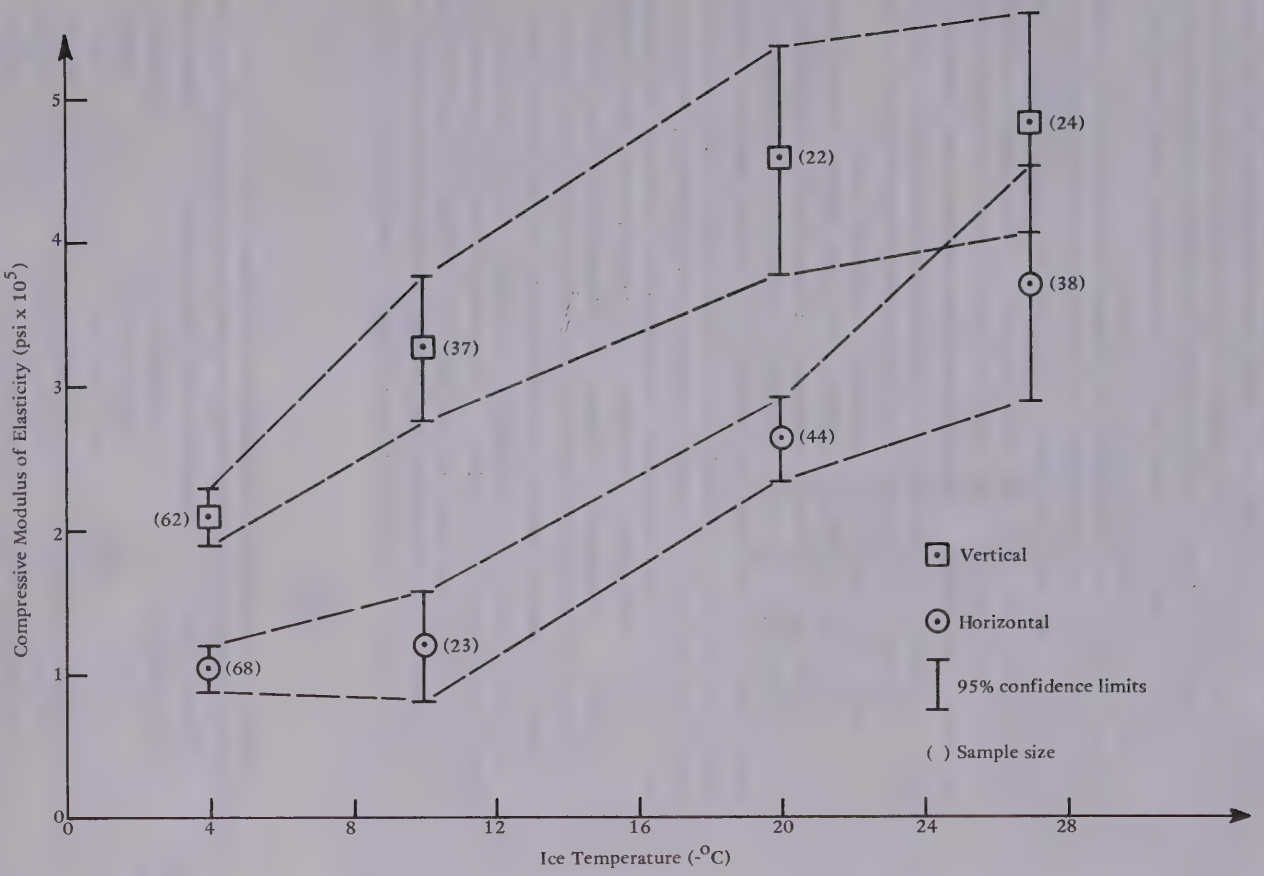

Figure 3. Compressive modulus of elasticity versus ice temperature.

Another method of determining the modulus of elasticity is to measure the strain at the location of the maximum fiber stress on sea-ice beams. These beams were the same ones tested for flexural strength. Bending deformations during laboratory tests were measured by an extensometer bonded to the underside of the beams, while in-the-field deflection was recorded by a linear voltage displacement transducer (LVDT) having a 6-inch stroke. Results from all modulus of elasticity beam testing are shown as a function of ice temperature in Figure 4.

Still another method for determining Young's modulus is a dynamic experimental method [6]. An ice specimen is vibrated by a transmitter, and either the velocity of the longitudinal waves or the fundamental transverse frequency is determined from the receiver output. The dynamic modulus of elasticity can be calculated from simple equations, if either the velocity or frequency is known. Dynamic modulus values are generally higher than those obtained by deflection measurement methods; therefore, average modulus of elasticity values for different temperature periods were selected as input to the finite element computer code.

There exists a modulus gradient across the ice sheet corresponding to the temperature gradient for each season. These modulus gradients, as well as their corresponding flexural strength values, are given in Table 1 for each seasonal period defined in Figure 1. These modulus gradient values can be assumed to vary linearly as a function of ice sheet thickness for practical application, with larger values corresponding to the top of the ice sheet. There is an apparent discrepancy between the moduli values shown in Table 1 and those plotted as a function of ice temperature in Figures 3 and 4. However, it must be remembered that Table 1 values represent averages obtained from both dynamic and deflection methods while Figures 3 and 4 depict results from two different deflection methods only. In addition to the flexural strength and modulus of elasticity properties listed in Table 1, Poisson's ratio (the ratio of transverse to longitudinal strain) is needed for determining the bearing capacity of an ice sheet. A constant value for Poisson's ratio of 0.33 was assigned on the basis of reported experiments indicating a range from 0.30 to 0.35.

Table 1. Material Properties of Sea-Ice

Seasonal Period	Ice Surface Temperature (^{o}F)	Modulus of Elasticity Gradient ($psi \times 10^{5}$)	Flexural Strength (psi)
1	-4 to 14	7.0 to 2.9	70.0
2	14 to 23	6.0 to 2.9	62.0
3	23 to 27	4.0 to 2.9	58.0
4	27 to 28.5	2.9*	40.0

* Isothermal condition.

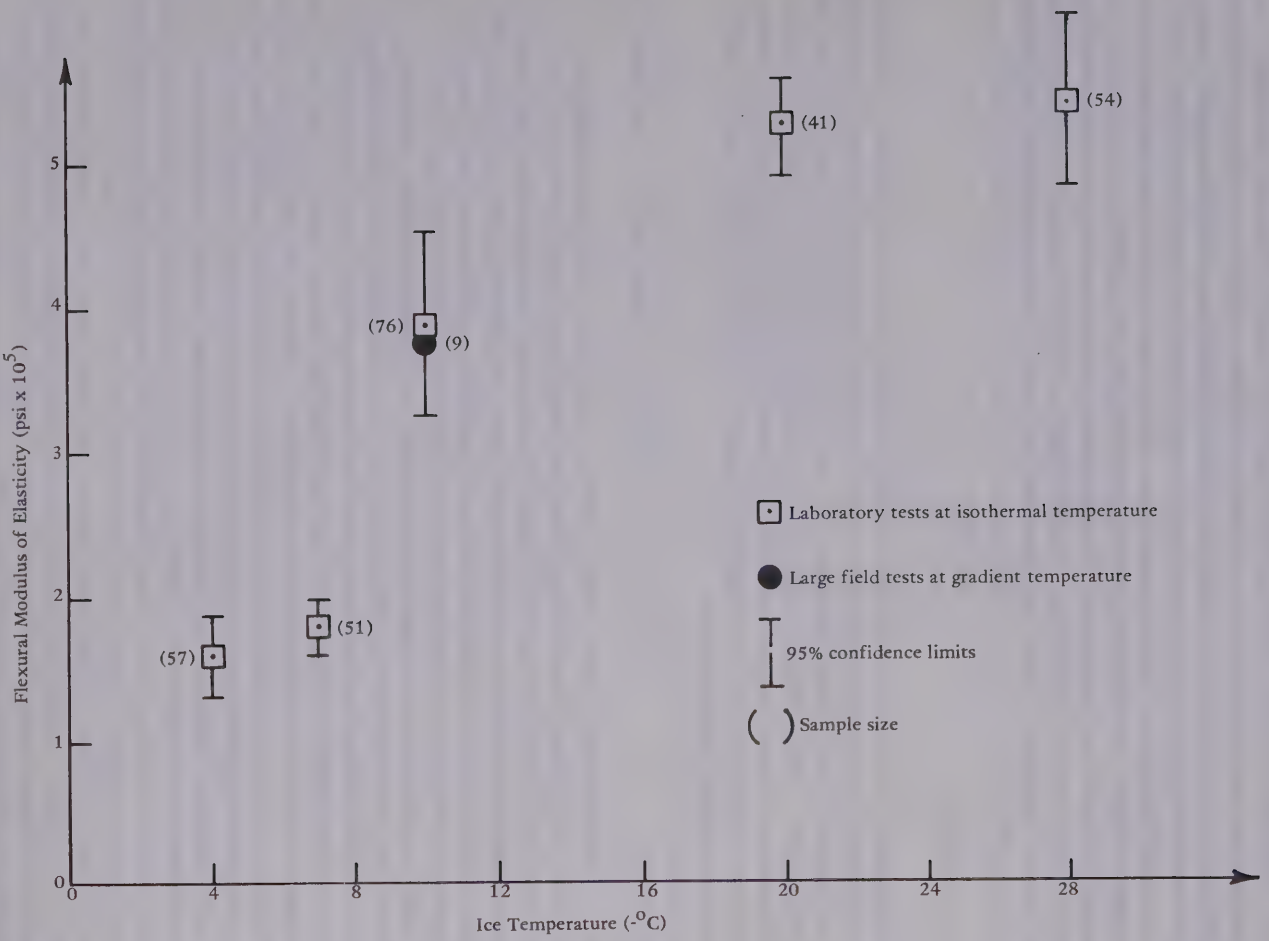

Figure 4. Flexural modulus of elasticity versus ice temperature.

ANALYTICAL METHOD

The main portion of the general axisymmetrical finite element computer code employed in this investigation was written by Wilson [7]. The formulation is based on the direct stiffness method with triangular or quadrilateral conical elements representing the axisymmetrical ice sheet. Generally, the ice sheet may have a complex configuration and can be considered as a layered medium. The constitutive relationships can be orthotropic, nonlinear, and temperature-dependent. External loading can be either structural or thermal in nature with an option to consider gravitational forces. In addition, subroutines are incorporated into the main computer deck to simulate a fluid foundation and to superimpose stresses from any combination of wheel or track configurations.

Fluid Foundation

Development of the simulated fluid foundation is achieved by calculating a vertical resistance proportional to the displaced volume and adding it to the global stiffness matrix of the solid for every node on the solid-fluid interface. In formulating the vertical resistance, compatibility of displacements requires off-diagonal terms as well as diagonal terms; all of these terms are determined by energy principles consistent with the finite element formulation.

Superposition

The superposition development determines the combined state of stress in an ice sheet resulting from an arbitrary configuration of circular loads. The principle of superposition has inherent limitations; first, the stress-strain relationships must be linear, and second, the ice sheet must be free of variations of material property and layer geometry with respect to any horizontal plane. Fortunately, typical ice sheets are composed of horizontal layers that have material property variations and temperature changes solely in the vertical direction. Moreover, the infinite extent of the ice sheet nullifies the effect of boundaries, confounding the superposition principle; hence, the only significant limitation is the restriction to linear stress-strain laws.

The process of determining the superimposed stress state begins by choosing a point in the ice sheet where the combined state of stress is to be calculated. Usually this point is located beneath a critical wheel or track on aircraft or vehicles. The chosen point is declared to be at the bottom of the ice sheet beneath the origin of an x-y rectangular coordinate system. Then, for each additional load from i^{th} other wheel or track circles, the load center is assigned the coordinates (x_i, y_i), and the local state of stress at (x_i, y_i) is transformed into an incremental stress contribution at the origin by using polar coordinates. This process is repeated until the stress contributions for each load are summed at the designated origin to yield the complete combined stress state. Finally, the principal stresses are calculated from this combined stress state.

Representation of an Infinite Boundary

For many applications an infinite expanse of ice is characteristic of the problem to be solved. In such cases defining an infinite expanse by an axisymmetrical solid of finite extent is justifiable only if the boundary radius is chosen large enough so that changes in the boundary condition do not appreciably alter the structural response. Preliminary investigations show that the structural response of typical ice sheets tends toward plate-theory behavior in the outer region, beginning several loading radii away from the load center. Consequently, the minimum boundary radius required may be determined in terms of the radius of relative stiffness, ℓ,

$$\ell = \sqrt[4]{\frac{E\,h^3}{12(1 - \upsilon^2)\gamma}} \qquad (1)$$

where E = Young's modulus
h = ice sheet thickness
υ = Poisson's ratio
γ = seawater density

In general, a boundary radius of 10ℓ with a fixed boundary condition will adequately represent an infinite ice sheet.

Input Parameters

The input requirements can be divided into two basic categories: (1) ice-sheet material properties, and (2) aircraft or vehicle loading conditions. In the first category the temperature is given for both the top and the bottom of the ice sheet, along with a corresponding modulus of elasticity and Poisson's ratio for each temperature. Also, the thickness must be estimated, as well as the density of the fluid foundation (in this case, seawater). For category 2 the number of circular loadings (e.g., wheels or tracks) and total load (weight of aircraft or vehicle) are required, along with such individual wheel or track circle characteristics as: (1) radius and pressure of load; (2) x-y coordinates (to locate each loading); and (3) fraction of total weight carried by an individual loading. An idealized ice sheet subjected to a circular load during seasonal period one is shown in Figure 5 where many of the input parameters are identified.

ICE-THICKNESS CURVES AND TABLES

After experiments to determine sea-ice material properties have been performed and a finite element model to predict sea-ice behavior has been developed, it is possible to calculate required ice thicknesses for aircraft and vehicular operations.

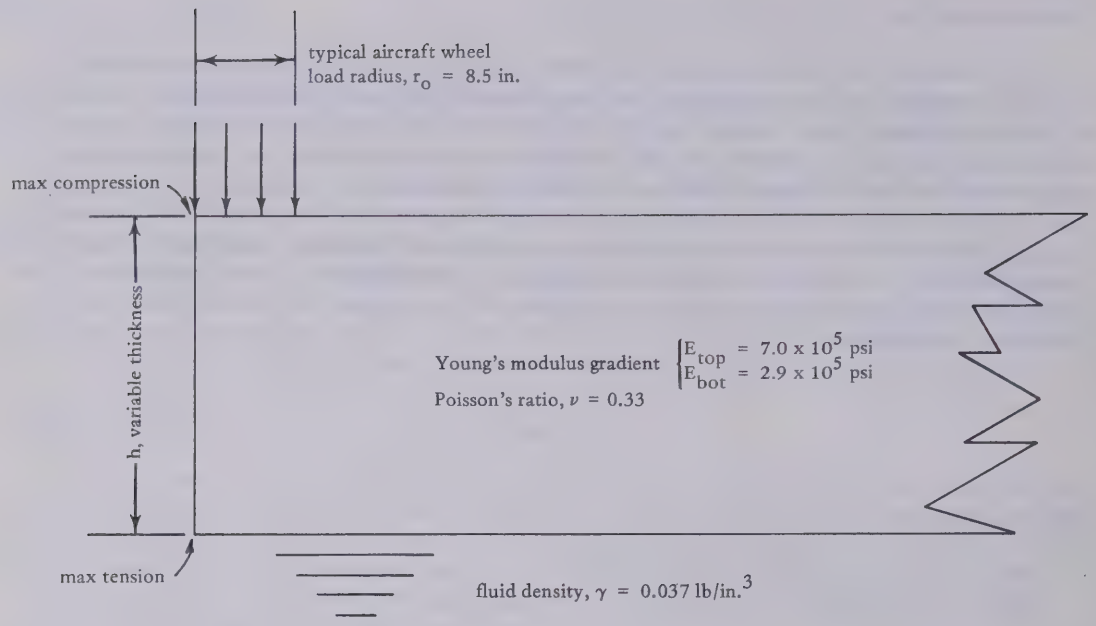
typical aircraft wheel
load radius, r_o = 8.5 in.
max compression
h, variable thickness
Young's modulus gradient E_{top} = 7.0 x 10^5 psi
E_{bot} = 2.9 x 10^5 psi
Poisson's ratio, ν = 0.33
max tension
fluid density, γ = 0.037 lb/in.^{3}

Figure 5. Idealized sea-ice sheet for seasonal period 1.

Updated aircraft load versus ice-thickness curves are presented in Figure 6. Previous curves from Reference 3 were calculated using classical plate theory and assuming no ice sheet temperature gradient. In Figure 6 curves for both C-130 and C-141 aircraft are shown for all four seasonal periods defined in Figure 1. Calculating these curves requires exercising the computer code in two series of repeated steps. Initially, the input parameters for a single seasonal period are selected from Table 1, and several ice-sheet thicknesses are assumed for this period. By performing computer iterations, tensile stresses are found at the bottom of the ice sheet for each specified thickness. This process formulates an aircraft load curve for a given seasonal period, and the entire cycle is repeated for the remaining periods. Period one curves for both aircraft are calculated from an allowable stress that is found by reducing the period one flexural strength by 30%, an effective safety factor of 1.20. All other curves reflect a reduction of 25% in their respective ultimate strengths, representing a safety factor of 1.15. Therefore, the allowable stress for period one is 70% of its ultimate flexural strength, while the allowable stresses for the other three periods become 75% of their respective ultimates.

Minimum ice-sheet thicknesses for vehicles and equipment combinations are given in Tables 2 and 3. Again, the iterative process is repeated for each seasonal period. However, for relatively constant loads (e.g., vehicles) the iterations converge to a single, tabular point rather than a curve

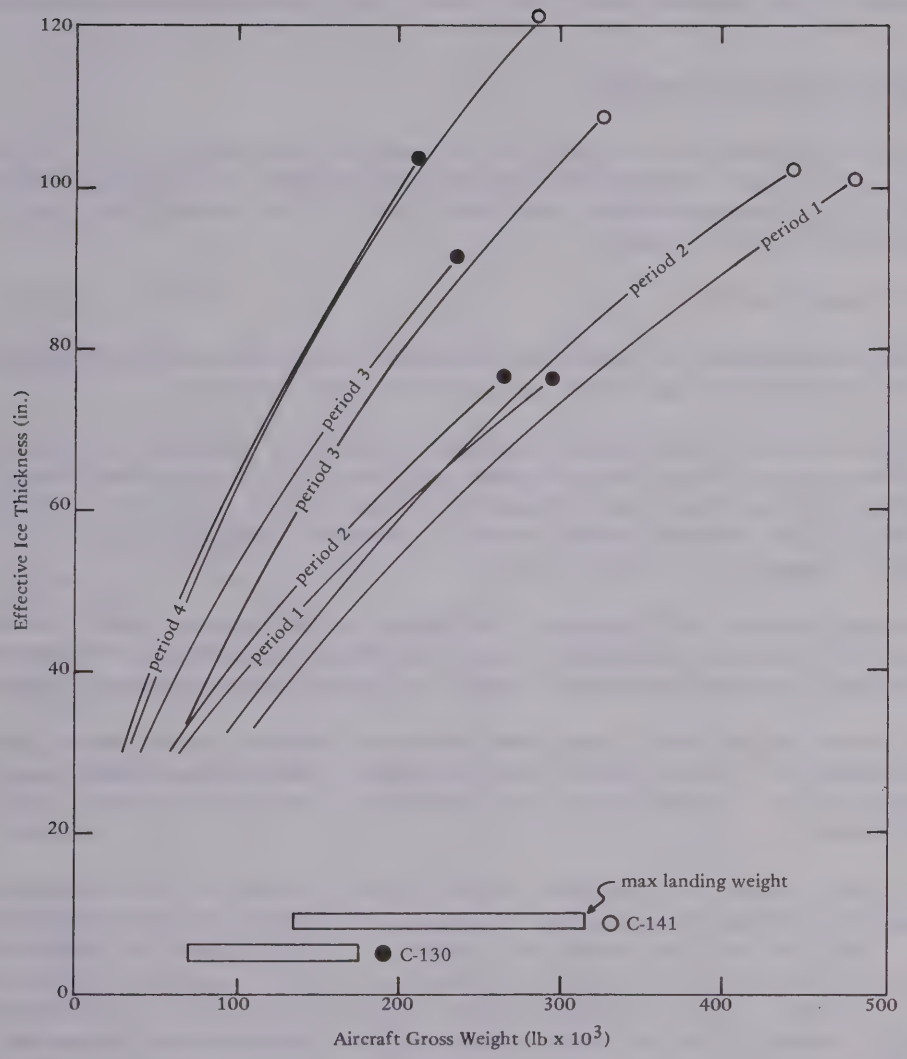

Figure 6. Load curves for both C-130 and C-141 aircraft over four seasonal periods.

in the case of aircraft, which have a wide range of load capacity. All vehicles and equipment combinations are grouped by function categories, and vehicle weights used for thickness calculations are given. Allowable stresses represent a sufficient reduction in failure strength to produce a safety factor of 1.50. These tables are meant to replace those in Reference 1 for tracked vehicles, sleds, and tractor-sled combinations.

OPERATIONAL FIELD PROCEDURE

Field procedure for aircraft and vehicle operation on the annual sea-ice sheet near McMurdo Station should include: (1) ice-thickness surveys; (2) ice-temperature stations; and (3) ice runway and road inspection and precautions.

Ice-Thickness Survey

The maintenance of complete, up-to-date ice-thickness surveys for all ice-sheet operating areas is necessary for safety.

1. At the start of the operating season (usually October), a detailed thickness survey should be made down each edge of the sea-ice runway, alongside the ice road, and around all other operating areas. Thickness stations on the runways should be at 1,000-foot intervals, with opposite stations staggered at midinterval.

2. During October and November, thickness measurements should be made at every station at 14-day intervals to provide thickness information. Field conditions may indicate a need for more frequency measurements.

3. Starting in December, the time interval between measurements should be decreased to 7 days, and by early January, daily measurements may be required if the ice conditions and aircraft operations warrant such surveillance.

4. Any soft, mush-ice skeletal layer at the bottom of the sheet should be subtracted from the measured thickness to obtain the effective thickness of the ice for the curves or tables. The thickness of this layer will vary considerably through the season. Until late December, this layer is normally new ice growth that has not completed solidification. By early January, the new growth should have disappeared; it may be replaced by a soft layer resulting from bottom deterioration. Because of this layer, the effective thickness of the ice is usually 2 to 6 inches less than the actual thickness. The thickness of the skeletal layer can only be determined by extracting cores from the ice with a 3-inch-diameter coring auger.

Table 2. Minimum Allowable Ice Thicknesses for Vehicles

Vehicle	Minimum Allowable Ice Thickness (in.)			
	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Small cargo/personnel (wheeled)				
1. Pickup, 1T-Dodge W300 (GVW = 9,000 lb)	11	13	17	21
2. Jeep, Kaiser 1414 (4,000 lb)	10	11	14	17
3. Truck, ambulance-Kaiser M725 (8,400 lb)	14	16	20	24
4. Bus, 4 x 4 — Fabco (15,260 lb)	15	18	23	29
5. Cargo/personnel-Nodwell 45TT (15,000 lb)	16	18	23	28
6. Crash/rescue-Nodwell 100TT (25,000 lb)	21	24	30	36
Small cargo/personnel (tracked)				
1. Personnel carrier-Nodwell RN110 (GVW = 27,500 lb)	17	21	28	34
2. Personnel carrier-Nodwell RN110 (50% load — 21,500 lb)	15	18	24	30
3. Personnel carrier-Trackmaster 601 (7,540 lb)	10	12	16	20
Truck, tractor				
1. Tractor, 10T-MIL M123A1C (28,100 lb)	24	27	34	41
2. Tractor, 10T-Fabco CT850 (15,200 lb)	16	18	23	28
3. Tractor, 5T-M52A2 (18,700 lb)	17	20	25	31
Crawler tractor				
1. Caterpillar D-4 STD (17,250 lb)	20	24	31	38
2. Caterpillar D-4 LGP (27,160 lb)	26	30	38	46
3. Caterpillar D-8 STD (67,600 lb)	43	48	60	71
4. Caterpillar D-8 LGP (85,000 lb)	44	48	59	71

continued

Table 2. Continued

Vehicle	Minimum Allowable Ice Thickness (in.)			
	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Load-handling equipment				
1. Caterpillar 950 (24,900 lb)	24	28	35	42
2. Caterpillar 966C (34,240 lb)	25	30	37	45
3. Caterpillar 955 STD (30,200 lb)	29	33	42	50
4. Caterpillar 955 LGP (33,500 lb)	23	26	33	41
Snow-removal equipment				
1. Snowblast R2200A (36,000 lb)	27	31	39	47
2. Cat 966 with snowblower attachment (43,470 lb)	31	35	44	52
3. Cat 950 with snowblower attachment (34,320 lb)	33	36	46	54
4. Road grader – Cat 12F (28,310 lb)	26	29	37	44
Special equipment				
1. Truck, wrecker – Fabco F800 (16,000 lb)	14	16	21	26
2. Crane, wheeled-Pettibone 70 (70,730 lb)	40	45	57	69
3. Drill, Trlr-Mtd-Mobile (14,800 lb)	17	19	25	30
Trailers				
1. Trailer, semi-12T Fruehauf (GVW = 25,500 lb)	26	30	37	45
2. Trailer, semi-20T Fabco (GVW = 29,770 lb)	27	31	39	47
3. Trailer, lowboy – 60T Military (GVW = 90,650 lb)	50	57	69	83
Sleds				
1. Sled, 10-ton-Otago (GVW = 29,000 lb)	19	22	29	35
2. Sled, 20-ton-Otago (GVW = 60,000 lb)	30	34	42	50

[a] Before October to late November.
[b] Late November to mid-December.
[c] Mid-December to early January.
[d] Early January to February.

Table 3. Minimum Allowable Ice Thicknesses for Equipment Combinations

Equipment Combinations	Minimum Allowable Ice Thickness (in.)			
	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Tractor-trailer				
1. 5T tractor (military) + 12T trailer (Fruehauf) (GVW = 56,000 lb)	27	31	39	43
2. 5T tractor (military) + 12T trailer (Fruehauf) (50% load = 44,000 lb)	23	26	34	41
3. 10T tractor (Fabco) + 20T trailer (Fabco) (GVW = 65,000 lb)	29	33	42	51
4. 10T tractor (Fabco) + 20T trailer (Fabco) (50% load = 45,000 lb)	23	27	34	41
5. 5T tractor (military) + 20T trailer (Fabco) (GVW = 69,000 lb)	29	33	42	52
6. 5T tractor (military) + 20T trailer (Fabco) (50% load = 49,000 lb)	24	27	35	43
7. 10T tractor (military) + 60T lowboy (military) (GVW = 180,000 lb)	52	58	74	88
8. 10T tractor (military) + 60T lowboy (military) (50% load = 120,000 lb)	41	46	58	70
Towed drill rig				
1. Caterpillar D-4 STD + Mobile drill B40L12 (32,000 lb)	21	25	31	36
2. Nodwell RN 110 + Mobile drill B40L12 (GVW = 42,300 lb)	21	24	32	38
Tracked vehicle — sled				
1. Caterpillar D-4 STD + 10T sled (GVW = 46,200 lb)	20	23	30	37
2. Caterpillar D-8 LGP + 20T sled (GVW = 145,000 lb)	45	51	61	72
3. Caterpillar D-8 LGP + two — 20T sleds (GVW = 205,000 lb)	56	62	74	88
4. Caterpillar D-8 LGP + three — 10T sleds (GVW = 172,000 lb)	49	55	66	78

[a] Before October to late November.
[b] Late November to Mid-December.
[c] Mid-December to early January.
[d] Early January to February.

Ice-Temperature Stations

The maintenance of a complete up-to-date temperature record of the ice sheet is necessary for a verification that the proper seasonal period is being used.

1. For ice-sheet thicknesses greater than 24 inches permanent stations to measure ice temperatures with thermocouples or thermistors should be established at five or more locations dispersed for general coverage of the entire operational area. Each permanent station should consist of two separate probes, one located 6 inches below the surface and the other, as a backup, 4 inches below the surface. At these depths daily fluctuating air temperatures should have little effect on obtaining consistent ice temperature data. These temperatures are compared with those given for the seasonal periods listed in Table 1. Temperature stations should be monitored two or three times a week during the operating season and preferably at the same time during the day.

2. For ice-sheet thicknesses less than 24 inches permanent stations need not be installed. No doubt such an ice thickness would represent an early season operational condition; therefore, governing tables for vehicular traffic probably would fall under period one. However, prior to operating on an ice sheet less than 2 feet thick, it is recommended that one take accurate thickness measurements as well as ice temperatures by inserting an accurate dial or mercury-bulb thermometer into the ice in a two- to three-inch drilled hole fitting thermometer stem. Snow or chipped ice should be packed around the thermometer to reduce air effects on ice temperatures. Measurements should be made as directed in the previous paragraph.

Ice Runway and Road Inspection

It is recommended that the ice runway and all roads be routinely inspected. If only the minimum ice thicknesses given in the curves and tables are measured, then the runway should be checked after every takeoff and landing, while the roads should receive daily reconnaissance. A log should be maintained of any cracks that occur and their condition, wet or dry. Development and spreading of cracks indicate the operations area has a near-capacity load, and further use should be suspended or continued only on an emergency basis at significantly reduced loads.

Ice creeps under sustained load; therefore, progressive deformation of the ice sheet can be expected beneath parked aircraft and vehicles, snow berms, and stored cargo. The limit of permissible deformation has not been defined as yet; however, it is recommended that any parked aircraft or vehicle be moved when the deflection has reached 8 to 10 percent of the ice sheet thickness. This limiting deflection represents the freeboard of an ice sheet, and flooding could occur if this value were exceeded. Any surface flooding over a loaded region could make

working difficult or impossible and workers unwilling to remain in the area. A level or transit should be available at all times to measure the deflection at the aircraft when questionable conditions are evident. To determine this deflection, the instrument should be located at least 300 feet from the aircraft, and measurements near the main wheel of the aircraft should be compared with those 600 feet from the aircraft.

When minimum ice thicknesses are encountered, no aircraft, whether landing, taxiing, taking off, or parked, should be closer than 500 feet from the edge of the ice sheet. No vehicle or equipment combination should be driven nearer than 300 feet from the edge of the ice sheet. Distances greater than these limits are preferred, if possible.

SUMMARY

This study represents an application of existing analytical techniques using current knowledge of sea-ice properties to redefine aircraft and vehicle operational criteria on the annual ice sheet at McMurdo Station, Antarctica. Mathematically modeling the ice sheet has been accomplished by a finite element computer code. The ice sheet was considered to be an axisymmetrical, elastic solid supported by a fluid foundation. The computer code has the capability of accounting for the ice-sheet temperature gradient, while calculating critical stresses for different multiple-load configurations. Since ice-sheet bearing strength is temperature-dependent, four seasonal periods, based on different ice-sheet temperature gradients, are defined by appropriate sea-ice material properties.

To calculate required ice thicknesses for aircraft and vehicle operations, stresses are determined for each wheel or load pattern, having assumed an ice-sheet thickness and temperature gradient. This process is repeated for other ice thicknesses; comparisons are made with allowable stresses, thus determining minimum required ice thicknesses. These minimum values generate curves for aircraft and single entries in the tables for vehicles and equipment combinations. The computation process is repeated again for each seasonal period.

Once the ice-thickness curves and tables are determined, proper field procedure is still necessary to operate safely on the ice sheet. Of course, both ice thicknesses and temperatures should be monitored; however, routine inspection of the ice-sheet surface should be made for the existence of cracks. These cracks should be recorded for length and location, and whether they are refrozen or ''working.''

Thus far, the analysis has been limited to elastic ice-sheet response; however, it is known that ice creeps under sustained loads. Although experimentation is currently underway to determine the viscoelastic response of sea ice, maximum allowable deformations have not been defined as yet. Therefore, it is imperative that long-term loads be monitored for excessive ice-sheet deflection.

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